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SUMMARY OF ROTOCHUTE DEVELOPMENT

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Nonr 901(00)

KAC REPORT NO. R-117
25 SEPTEMBER 1956

the KAMAN Aircraft Corporation

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    A summary of results of research under the subject contract including a discussion of the objectives and attainments to date and a presentation of criteria and data for rotochute design.

1/11/57 R. C. Jones for S. S. SHERBY

Office of Naval Research (Code 461)

CONFIDENTIAL

THE KAMAN AIRCRAFT CORPORATION

BLOOMFIELD, CONNECTICUT

Contract No.
NONR 901(00)

Report No. R-117
Date: 25 September 1956

SUMMARY OF ROTOCHUTE DEVELOPMENT

"This document contains information affecting the National Defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law."

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DEFINITION OF SYMBOLS

W = Gross weight in lbs.

S = Disc area in lb./ft.^{2}

$= \pi R^2$

R = Rotor radius in ft.

V = Velocity along flight path in ft./sec.

σ = Rotor solidity = ratio of blade area to disc area.

$= \frac{bc}{\pi R}$

b = Number of blades

c = Blade chord in ft.

δ = Blade mass parameter.

$= \frac{4 \bar{y} W_b}{g \rho c R^2}$

$\bar{y}$ = Blade spanwise center of gravity location expressed as a fraction of radius.

W_b = Weight of blade.

g = Acceleration due to gravity = 32.2 ft./sec.^{2}

ρ = Density of air = .00238 slug/ft.^{3} at sea level.

C_{D_R} = Rotor disc drag coefficient.

$= \frac{W/S}{1/2 \rho V^2}$

Ω = Rotor rotational speed in rad./sec.

N	=	Rotor rotational speed in r.p.m.
n_x	=	Longitudinal acceleration in g's.
S_c	=	Compressive strength of honeycomb in $lb/in.^2$
A	=	Cross section area of shock absorbing nose in $in.^2$
X	=	Effective uniform crushing length of honeycomb nose in ft.
l	=	Actual equivalent uniform length of honeycomb nose in ft.

I. INTRODUCTION

The Kaman Aircraft Corporation has been engaged under the terms of contract NONR 901(00) in development of the Rotochute, a rotary-wing aerodynamic retarder operating on the principle of the autogyro, for use in the Marine Corps supply drop program. This Rotochute is being developed around the 500 lb. capacity Marine Corps M-2 high-speed aerial delivery container. The object of this development is to safely deliver to the ground 500 lb. of rations, ammunition, equipment or other military supplies after release from the external rack of a jet fighter at an altitude of 700 ft. or above and at speeds up to 600 knots.

The purpose of this report is to summarize the current status of development under this contract and to discuss some of the important considerations affecting Rotochute design.

II. SUMMARY

Research performed under Contract NONR 901(00) to date has resulted in the following accomplishments:

1. Development of empirical data concerning the performance of autorotating rotors in vertical descent over a range of disc loadings from 1.5 to 8.0. These data, obtained from wind-tunnel and flight testing, are most extensive in the lower disc loadings, but a sufficient number of high disc loading points have been obtained to allow prediction of over-all performance in terminal descent over the range mentioned above to a degree of accuracy satisfactory for design purposes. Work now in process under another contract is expected to result in establishment of the theoretical relationships involved in low-speed performance, allowing development of a reliable analytical method for computing the effect on performance of the various physical and operational rotor parameters.

2. Development of an analytical method for computing rotor performance during high-speed deployment and deceleration.

3. Development of an analytical method for computing the trajectory of rotochute systems released at various speeds and altitudes.

4. Development of means for absorbing ground impact shock of rotochute delivery systems.

5. Development, experimentally and analytically, of means of obtaining dynamic stability of rotochutes in equilibrium descent.

6. Development of means for obtaining stable separation of external stores from high-speed aircraft.

7. Development of an automatic rotor governor for maintaining the rotor speed within desired limits throughout the range of airspeed from high subsonic release to terminal descent.

8. Development of a system of telescoping rotor blades to allow large rotor diameters to be stowed more compactly.

9. Development of several sizes and capacities of flight research articles with the following capabilities:

   a. 75 lb. gross weight, 7 ft. diameter telescoping blades, 38 ft./sec. rate of descent, demonstrated to 520 knots release speed.

b. 60 lb. gross weight, 4 ft. diameter rotor, 60 ft./sec. rate of descent, demonstrated to 450 knots release speed but believed capable of use at considerably higher speeds.

c. 950 lb. gross weight with 500 lb. payload, 24 ft. telescoping blades, 40 ft./sec. rate of descent, demonstrated to 250 knots release speed.

d. 900 lb. gross weight with 500 lb. payload, 14.5 diameter rotor, 70 ft./sec. rate of descent, demonstrated to 490 knots release speed but believed capable of considerably higher speed. Flight test results of this unit are summarized on Table I, with photographs of one article after a successful 490 knot flight included as Figures 1 and 2.

High speed tests on the above articles have been limited by the maximum speed of the available flight test aircraft, a government furnished F9F-5.

In addition to the successful rotochute systems described above, the general rotochute results obtained under this contract have made possible the use of the rotochute in other applications within the United States military establishment.

Under Bureau of Ordnance contract, a rotochute was designed for the 6" - 47 illuminating projectile, a star shell fired from Naval 6" guns. During firing tests of 25 of these units, 23 successful rotochute deployments were obtained at a Mach number of 1.25 at 3,000 ft. altitude, demonstrating the supersonic potentialities of the rotochute. Development of this application toward eventual service use in this and other ordnance is continuing.

The rotochute has also been successfully demonstrated in model form for use in bulk cargo delivery. A 4 ft. diameter rotochute was attached to a length of cable made fast to a 5 gal. gasoline can filled with water and placed on the roller conveyor of a Marine Corps R4Q aircraft. At the target area, the folded rotochute was released out the open cargo door. Upon opening in the airstream, the rotochute dragged the load out of the aircraft and delivered it to the ground at a measured rate of descent of 60 ft./sec. Upon recovery, the can was found to be still water-tight and undamaged except for a few minor dents.

Another promising application for the rotochute is in aerial delivery of various electronic devices intended for ground operation. An Air Force contract has been received for one such application.

It is believed that the work accomplished under this contract to date has definitely established the soundness of the rotochute principle for highspeed aerial delivery of various types of stores and has demonstrated that this principle can be achieved in practice. A rotochute system has been developed which is believed to be capable of meeting the present day performance requirements of the Marine Corps highspeed supply drop mission but which, it is felt, can be considerably improved in terms of performance, size and weight with additional refinement. The understanding of rotochute design criteria provided by the general rotochute research conducted under this contract and currently being extended under contract to another government agency should provide the basis for this refinement.

III. DISCUSSION

A. Performance

1. Low Speed

a. Required Rate of Descent

Inasmuch as the complexity, size and weight of the final rotochute for any given application will be influenced strongly by the necessary rate of descent, it is economical to design for the highest rate of descent tolerable for the mission. For supply drop applications, the governing parameter is not rate of descent as such, but impact acceleration. While few data are available at the present time on fragility of the various types of stores which may require air delivery, Quartermaster Corps Food and Container Institute personnel have estimated on the basis of their experience that the most vulnerable stores, which have been found to be liquids in cans, will withstand approximately 80g deceleration without damage. Electronic equipment is designed for between 100g and 300g depending on the anticipated service. Clothing, tools and most ammunition will withstand even higher accelerations. A maximum design deceleration at ground impact of 60g has therefore initially been chosen for the Marine Corps Rotochute.

Unless provisions are made in the container itself for absorbing the energy of deceleration, there will be no reliable correlation

between rate of descent and impact acceleration. Obviously, a rigid container striking a hard surface would result in objectionably high impact shock at the lowest possible rate of descent. A softer landing surface might allow very high rates of descent without unacceptable shock loads. Inasmuch as the character of the landing surface cannot be controlled or predicted under field conditions, a satisfactory alternative is to build into the nose of the container itself provisions for shock attentuation to the desired level independent of landing surface.

Many means for doing this have been utilized in past programs by various agencies. Hydraulic shock absorbers, spikes, and resilient or crushable nose cones have been used with various degrees of complexity, cost and success. One of the most effective, cheapest and lightest means of absorbing the required energy appears to be use of paper, cloth, or aluminum honeycomb oriented so that the cells are crushed as columns by the kinetic energy of impact, as described in references 1 through 5. Compressive tests of honeycomb material show a characteristically flat load-deflection curve as shown on Fig. 3 for a typical grade of paper honeycomb. It is seen that 75% of the thickness of the material crushes at approximately constant load, allowing large dissipation of energy at a minimum value of load. Reference 1 presents a method for designing

shock absorbing noses from similar materials. When the stress-strain curve is flat as in Fig. 3 this method is simplified as follows:

$$\text{Maximum deceleration factor } n_x = \frac{S_c x A}{W}$$

where n_x = longitudinal deceleration factor in g's.
S_c = ultimate compressive strength of honeycomb in lb/in.^{2}
A = cross sectional area of container nose in in.^{2}
W = gross weight of rotochute in lb.

For a container of given cross-sectional area such as the M2, crushable material of suitable compressive strength is chosen so that n_x will be within allowable limits. It is noted that n_x is independent of rate of descent but is only affected by honeycomb strength, gross weight of the unit, and cross section area of the nose. For example:

For the M2 container, assuming W = 900 lb. and using a nose cylinder of TIP-2 paper honeycomb,

S_c = 125 psi from Fig. 3
A = 347 in^2
and $n_x = \frac{125 \times 347}{900} = 48.3g$ which is sufficiently within the 60g limit previously selected to provide an allowance for crushing the aluminum shell used to house the honeycomb.

Length of the required nose is determined by the amount of kinetic energy which must be absorbed, which in turn is dependent on the

gross weight and the rate of descent. Since work done in crushing the honeycomb must be equal to the kinetic energy of the body just before impact:

$$S_c A x = 1/2 \frac{W}{g} V^2$$

where: x = effective uniform crushing length of honeycomb nose in ft.
V = rate of descent in ft/sec.
g = acceleration due to gravity = 32.2 ft/sec.^{2}
Other symbols are as before.

For the M2 container, using figures assumed above:

S_c = 125 lb/in.^{2}
A = 347 in.^{2}
W = 900 lb.
g = 32.2 ft/sec.^{2}
and x = .000321 V^2

Thus, the required effective crushing length of the honeycomb is proportional to the square of the rate of descent. Actual length of the nose must, however, be somewhat greater, since the entire thickness of the honeycomb is not crushed at constant load. From Fig. 3 it is seen that the load increases rapidly beyond the 75% crushed point as the remainder of the material bottoms.

Therefore, $l = \frac{X}{.75}$

where l = required length of actual nose cross section

or $l = \frac{.000321\ V^2}{.75} = .000428\ V^2$

l is plotted against V on Fig. 4.

Since lower rates of descent will require larger, heavier, more expensive rotors, the longest practical nose should be fitted to allow the highest possible rate of descent. Relatively high rates of descent also have the advantage of reducing the side-drift angle in a wind, thus improving efficiency of utilization of the shock absorbing nose and minimizing aiming inaccuracies.

The above analysis is based, for the sake of simple illustration, on use of a right circular cylinder of uniform compressive strength. For an actual nose cone of parabolic or ogival shape, it is possible to approach the energy absorbing performance of the uniform cylinder by making the honeycomb filler in layers of varying density whose compressive strength is inversely proportional to cross-section area. The actual nose cones used on flight No. 1223 and 1224 of Table I were of this general type. A cross-section of one is shown on Fig. 5 after flight 1224. The after three layers of largest cross section area were of 3/8" x .002" aluminum honeycomb of 148 psi compressive strength and were originally 10" thick,

requiring 51g to crush. The remainder is of 3/8" x .004" aluminum honeycomb of 274 psi compressive strength. Due to differences in cross-section area, the g's required to crush these layers vary from 10 for the smallest to 85 for the largest. This rotochute landed on firm unimproved soil, making a 9" deep hole. The Kinetic energy was absorbed by the resistance of 9" of soil and the observed partial crushing of the four layers of honeycomb. The strongest layer to show crushing has a strength of 51g so it is concluded that this was the maximum deceleration of the rotochute. Had the landing been on a hard surface such as rock or concrete, more of the stronger layers of honeycomb would have crushed and the deceleration would have been proportionally higher but never higher than the strongest layer, or 85g. Using a wider range of honeycomb density would allow further improvement in absorption uniformity. Aluminum honeycomb, rather than paper, was used because of its improved moisture resistance. Paper honeycomb in roughly the same strength range is available, is slightly cheaper, and could be substituted if desired.

b. Attainable Rates of Descent

(1) Flight test and wind-tunnel test results reported in references 6 through 9 show that rotor disc drag coefficients of 1.1 can be obtained reliably in terminal descent. Rotor disc drag coefficient is defined as follows:

$$C_{D_R} = \frac{W/S}{1/2 \rho V^2}$$

where C_{D_R} = rotor disc drag coefficient
W = gross weight of vehicle in lb.
S = disc area in ft.^{2}
= πR^2
R = rotor radius in ft.
V = rate of descent in ft/sec.

For a given rotochute then

$$V = \sqrt{\frac{W}{1/2 \rho C_{D_R} \pi R^2}} = \frac{1}{R}\sqrt{\frac{W}{1/2 \pi \rho C_{D_R}}}$$

for the M2 Rotochute, V is plotted against R on Fig. 6.

Fig. 6 taken together with Fig. 4 shows that for the M2 Rotochute, a 6 ft. radius will result in 77.5 ft/sec. rate of descent which will require a crushable nose 2.6 ft. long while a 7 ft. radius results in 67 ft/sec. and requires a 1.9 ft. nose. Either of these would appear practical from a design standpoint.

The dependence of rotor disc drag coefficient on rotor tip speed and solidity is shown on Fig. 7. This is a graphic presentation of available empirical performance data both wind-tunnel and flight test. Although some scatter due to measurement inaccuracies, blade surface condition and flight conditions is

evident, the correlation between C_D and the parameter $\frac{V}{\Omega R\sqrt{\sigma}}$ is quite good and shows that for a rotor of given solidity the drag coefficient is dependent on the ratio of descent velocity to tip speed.

Thus, for a drag coefficient of 1.1 to be obtained a value of $\frac{V}{\Omega R\sqrt{\sigma}} \leq .5$ is required. For the forementioned 7' radius rotor of .106 solidity and 67 ft/sec. descent speed:

$$\Omega R = \frac{V}{.5\sqrt{\sigma}} = \frac{67}{.5(.325)} = 412 \text{ ft/sec.}$$

$$N = \frac{60\,\Omega R}{2\pi R} = \frac{60(412)}{2\pi(7)} = 560 \text{ r.p.m.}$$

If for structural or stability reasons, a lower r.p.m. must be used, the drag coefficient will be lower according to the relationship of Fig. 7, resulting in higher rate of descent. The variation of rate of descent with r.p.m. for the above described Rotochute is presented on Fig. 8. This explains the variation of touch-down speeds between the flights of Table I. However, it was demonstrated in Flight 1224 that even at 77 ft/sec. touch-down speed, the shock absorbing nose cone kept impact loading to an acceptable value.

2. High-Speed Performance

Reference 6 presents a method for computing the thrust of a rotochute at high speed during deployment and deceleration. This method was approximated in greatly simpler mathematical form in Reference 7 and shown to agree to a satisfactory degree of accuracy with the high-speed wind-tunnel results of Reference 10. Using this method at high speed and the low-speed wind-tunnel tests of Reference 8 for the low-speed regime, total drag of the M2 Rotochute is calculated for air speeds up to 900 ft/sec. and presented on Fig. 9.

3. Rotochute Flight Path

Time histories of velocity, altitude and range were calculated by the method of Reference 6 using drags of Fig. 4 for a 6 ft. radius rotochute deployed at 760 ft/sec. and a 7 ft. radius rotochute deployed at 845 ft/sec.

Fig. 10 presents the results of the flight path calculations for the 6 ft. radius rotochute. It is seen that an altitude of at least 1,000 ft. is required to bring the rotochute into vertical descent at the computed rate of descent of 77.5 ft/sec. The rotochute of this configuration which was tested in Flight 1220 of Table I was deployed at 850 ft. altitude. From Fig. 10 this rotochute would be expected to strike the ground 10.4 sec. after launching at

which time it should be not quite vertical and should be traveling at approximately 85 ft/sec. Measured flight time of the test rotochute was 10.0 sec. and it was not quite vertical upon impact. Correlation between test and computed trajectory information is, therefore, seen to be quite good.

Although it was seen in Section 1b above that the terminal velocity of 77.5 ft/sec. for the 6 ft. radius rotochute could be accommodated with a sufficiently long crushable nose, Fig. 10 shows that the necessary altitude exceeds by 300 ft. that specified for the mission. While this could be improved by increasing the rotor r.p.m., it is likely that spiral stability difficulties would be encountered. Therefore, a larger rotor diameter should be used.

Accordingly, the flight path for the same rotochute at the same rotor r.p.m., but with 7 ft. radius blades was calculated from a deployment speed of 845 ft/sec. and is shown on Fig. 11. It is seen that terminal conditions are established after 9.0 sec. at a velocity of 66 ft/sec., a range of 2,750 ft. and after an altitude loss of 550 ft. This rotochute, then, would appear to meet the performance requirements of the intended mission.

A very similar configuration (7.25' radius, 475 r.p.m.) was tested on Flight 1224, summarized on Table I. Total flight time was 11.0 sec.

Analysis of movie film showed that terminal conditions were established 1.7 seconds before touchdown, making the trajectory time 9.3 sec. as compared with 9.0 sec. of Fig. 11. Also if the final touchdown speed is assumed equal to the average rate of descent, the altitude loss should have been approximately 9.3 x 77 = 720 ft. as compared with 550 ft. of Fig. 11. This degree of increase in trajectory would be attributable to the lower 475 r.p.m. rotor speed. As noted in Table I, however, the indicated altitude corrected for F9F-5 position error at release less the altitude remaining upon establishment of terminal conditions is approximately 1,000 ft. The large discrepancy between average descent rate on this basis and the measured touchdown speed would suggest that either the rotochute was released in a nose-down attitude or at a lower altitude than recorded due to aircraft altimeter lag, improper position correction, or inaccuracy in pilot's altimeter reading. In view of the high speeds and short times involved, the accuracy of measurement required for precise experimental trajectory determination is not obtainable by the semi-qualitative stop watch and altimeter reading methods used heretofore, and an Askania Photo-theodolite range would be required to determine conclusively the minimum operating altitude of the present rotochute. However, it is seen that the computed trajectories are at least approached in actual flight.

B. Stability

1. Static Stability

An external store mounted under the wing of a high-speed aircraft is located in a slipstream which is curved in the vertical plane by the upwash ahead of the wing and the downwash behind it. Further distortion of the free stream is caused by flow around the fuselage, inlet ducts, and other protuberances in the vicinity of the store. Rather large moments, therefore, may be acting upon the body which, upon release, produce angular accelerations, velocities and displacements of the body. As the body leaves the vicinity of the aircraft, the slipstream straightens out and the body must then align itself with the new relative wind direction. This disturbance and subsequent realignment takes the form of an oscillation which must be well damped to allow reliable opening of the Rotochute and prevent high cyclic blade bending moments.

During early flight test development of the full-scale Rotochute, blade failures were being experienced which might have been partly or wholly caused by excessively high cyclic bending moments during the damping oscillation. To allow rotor operational development without this complicating factor, stabilizing fins were fitted to the Rotochute which were as large as possible within the clearance envelope of the F9F-5 aircraft. These fins provided a high enough degree of aerodynamic stability and damping to produce a dead

beat damped oscillation with half-period of the order of the blade opening cycle time. While no blade failures have been experienced subsequent to installation of these large fins, certain changes in the rotor governor mechanism were made simultaneously. Subsequent full-scale wind-tunnel tests, reported in Reference 8, have shown that these governor changes could have been an important factor in satisfactory blade performance. It is, therefore, quite possible that a substantially smaller degree of static stability would prove satisfactory.

In view of the lack of aerodynamic cleanliness aft of the rear bulkhead in the present design, it was felt that perhaps even the present degree of stability could be attained with somewhat smaller fins by the use of streamlining to permit smoother flow of free stream air around the fins, increasing the local dynamic pressure. It was also desired to determine the present amount of static stability and drag quantitatively to provide a basis for eventual package refinement.

Accordingly, 1/3-scale models of the present Rotochute and one with streamlined afterbody and smaller fins were constructed for wind-tunnel testing. Both configurations were tested with and without blades, fins and other components to allow determination of the contribution of each part to drag and static stability. Results of

these tests, presented in Reference 11, indicate that improvement of the flow around the rear of the Rotochute body makes approximately 15% reduction in fin area possible for the same degree of static stability. Further, a 20% decrease in drag of the unit as carried on the aircraft bomb rack may be expected.

Future development toward minimizing the envelope of this supply drop system, therefore, should provide first for determination of the minimum values of static stability and aerodynamic damping required for satisfactory Rotochute deployment, and second for location of the necessary fin area in regions of as high local dynamic pressure as possible. Appropriate use of streamlining should be made to improve flow conditions and reduce drag.

2. Dynamic Stability

When dynamic instability is encountered with a Rotochute, the characteristic mode is a divergent spiral resulting in side drift at touchdown and disorientation with respect to shock absorbing provisions in the nose of the body. For satisfactory performance, therefore, the Rotochute must be dynamically stable.

Extensive model flight tests were performed in the early phases of research work under this contract to explore the factors influencing spiral stability. This work is reported in Reference 6. It was

found that body center of gravity location, rotor disc loading, blade mass and spanwise mass distribution and rotor r.p.m. all had an important effect on spiral stability. Since development of the Kaman rotor speed governor, this device has been used to control spiral stability through rotor r.p.m.

To better understand the factors involved and to establish design criteria which might provide stability over a wider range of rotor speeds, equations of motion of a Rotochute in vertical descent in four degrees of freedom were written and solved with the analog computer for a wide range of important parameters. This work is presented in Reference 7. The relationship between the rotor static stability derivative and rotor damping parameter was found to be the determining factor in dynamic stability. This relationship in turn is influenced chiefly by blade coning angle, higher coning being accompanied by increased stability.

It has been found from flight tests that the analytical method of Reference 7 reliably predicts the degree of dynamic stability for a particular Rotochute when experimentally measured values of static stability derivatives are available. Work is currently under way under another contract to develop methods for theoretically calculating values of these derivatives for Rotochute design purposes. It is known from the above referenced work, however, that light

blade construction, particularly at the tip, contributes to Rotochute stability and that when difficulty is encountered, a small reduction in rotor r.p.m. has a powerful stabilizing effect.

Flights 1221 through 1224 of Table I show the effect of r.p.m. on spiral stability on otherwise similar rotochutes. As r.p.m. was reduced from 525 to 500 to 475, stability was improved from severe instability to mild instability to positive stability. The effect of this r.p.m. reduction on performance is also indicated, rate of descent increasing from 62 to 63 to 77 ft/sec. It would, therefore, appear to be advantageous to increase the coning angle by lighter more efficient blade construction to allow use of the higher r.p.m.'s.

C. Rotor Speed Governor

As evidenced by References 8 and 9, a fixed pitch Rotochute operating in the turbulent flow autorotative regime, which is characterized by high ($\approx$ 1.1) rotor disc drag coefficients, operates at an essentially constant tip speed to inflow velocity ratio of the order of $\frac{2}{\sqrt{\sigma}}$ where σ is rotor solidity or the ratio of blade area to disc area. In order to provide the most efficient operation possible in terminal descent, a blade angle must be chosen which will insure operation in this regime. Under high-speed deployment and deceleration conditions, this same tip speed/inflow velocity ratio will of course apply, resulting in prohibitively high drag and rotor speed for which it would be impossible or at least uneconomical to design.

At higher blade angles, once autorotation is established, it is possible to operate in the windmill brake state, characterized by very much lower tip speed/inflow velocity ratios but also much smaller drag coefficients. While this state allows reasonable high-speed drag and design r.p.m., it requires nearly double the disc area for equivalent terminal rate of descent.

The Kaman rotor speed governor resolves this dilemma by causing the blade pitch angle to be responsive to rotor r.p.m. and airspeed so that the windmill brake state is maintained at all speeds much above

terminal velocity. As terminal speed is approached, the blade angle reaches a low enough value to cause transition to the turbulent flow state, accompanied by high drag coefficient and a higher r.p.m.

While the governor, consisting fundamentally of a spring loaded feathering hinge, is simple in design, its function, involving interaction of inertial and aerodynamic forces, their distributions, and their effect on the flow conditions around the blade, is not. Governor performance has not yet been reduced to the mathematics of servo analysis, although doing this will be an important part of a current Rotochute research program being conducted for another government agency.

Accordingly, governor design has been conducted empirically by means of truck and airplane tow tests for small models and the wind-tunnel tests of Reference 8 for a 12 ft. diameter Rotochute. Tests of this sort have established the approximate hinge locations, spring rates and preloads necessary to obtain a desirable variation of rotor r.p.m. with speed for each application. Final adjustment has been arrived at through flight test experience.

IV. CONCLUSIONS

Research and development conducted to date under Contract NONR 901(00) and discussed herein has led to the following conclusions:

1. With proper design of shock absorbing provisions in the nose of the M-2 container, 500 lb. of general supplies can be safely delivered to the ground by the present design Rotochute.

2. Rotochutes designed for this mission have been successfully deployed at speeds up to 490 knots.

3. A rotor speed governor is required to permit both reasonable high-speed operation and efficient low-speed performance. Such a governor has been developed and successfully demonstrated.

4. Control of rotor r.p.m. is essential to dynamic stability. Proper governor setting will prevent spiral divergence. Design factors contributing to stability have also been determined.

5. The present stabilizing fin arrangement provides satisfactory high-speed separation characteristics, but may be larger than necessary.

6. Continued refinement of the present design should allow substantial reduction in size and weight of the Rotochute and further improvement in performance.

TABLE I

FLIGHT TEST SUMMARY - 500# CAPACITY ROTOCHUTE

Flight Number	1220	1221	1222	1223	1224
Date	5/22/56	5/22/56	5/22/56	6/26/56	6/26/56
Gross Weight	906.2 lb.	911.3 lb.	920.6 lb.	901.0 lb.	901.5 lb.
Payload	500 lb.	500 lb.	500 lb.	500 lb.	500 lb.
Rotor Diameter	12.0 ft.	14.0 ft.	14.0 ft.	14.5 ft.	14.5 ft.
Disc Loading	7.9 lb/ft.^{2}	5.9 lb/ft.^{2}	5.9 lb/ft.^{2}	5.4 lb/ft.^{2}	5.4 lb/ft.^{2}
Solidity	.124	.106	.106	.102	.102
Rotor Speed, Nominal	485 r.p.m.	525 r.p.m.	500 r.p.m.	475 r.p.m.	475 r.p.m.
Governor Spring Rate	1150 lb/in.	1150 lb/in.	1150 lb/in.	1150 lb/in.	1150 lb/in.
Governor Spring Preload	430 lb.	1000 lb.	430 lb.	0 lb.	0 lb.
Deployment Speed, Pilot's Data	450 kts.	485 kts.	400 kts.	320 kts.	490 kts.
Deployment Altitude, Pilot's Data	850 ft.	1133 ft.	1050 ft.	1330 ft.	1160 ft.
Time for Drop, Timed	10.0 Sec.	12.5 Sec.	14.0 Sec.	16.5 Sec.	11.0 Sec.
Descent Speed, Average Computed	85 ft/sec.	90 ft/sec.	75 ft/sec.	30 ft/sec.	105 ft/sec.
Touchdown Speed, Analyzed from Film	94 ft/sec.	62 ft/sec.	63 ft/sec.	77 ft/sec.	77 ft/sec.
Stability	Stable	Severe Spiral	Moderate Spiral	Stable	Stable
Attitude Angle at Ground Impact, from Film	60°	45°	60°	90°	90°
Damage, Other than to Nose Cone and Rotor Blades	Severe	Severe	Moderate	Superficial	Superficial
Comments	Trajectory, rather long- not suitable for low altitude deployment- higher rpm or lighter disc loading required- deployment and rotor operation satisfactory.	Short trajectory- very rapid deceleration, losing nose cone- deployment and rotor operation satisfactory- severe spiral instability indicates lower rpm required- rate of descent satisfactory- discrepancy between average rate of descent and touchdown speed suggests diving release or lower altitude than recorded.	Deployment, rotor operation, trajectory and rate of descent satisfactory- mild spiral instability indicates lower rpm required- 60° attitude was result of spiral causing inefficient utilization of shock absorbing nose, hence moderate damage to unit.	All flight characteristics satisfactory- landed in shallow water and stuck in mud- nose cone uncrushed- terminal conditions established within 500 ft.- impact less than 10g.	All flight characteristics appeared satisfactory- discrepancy between average rate of descent and touchdown speed suggests diving release or lower altitude than recorded- condition of crushed aluminum honeycomb nose cone indicated 51g maximum impact.

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Fig. No. 1

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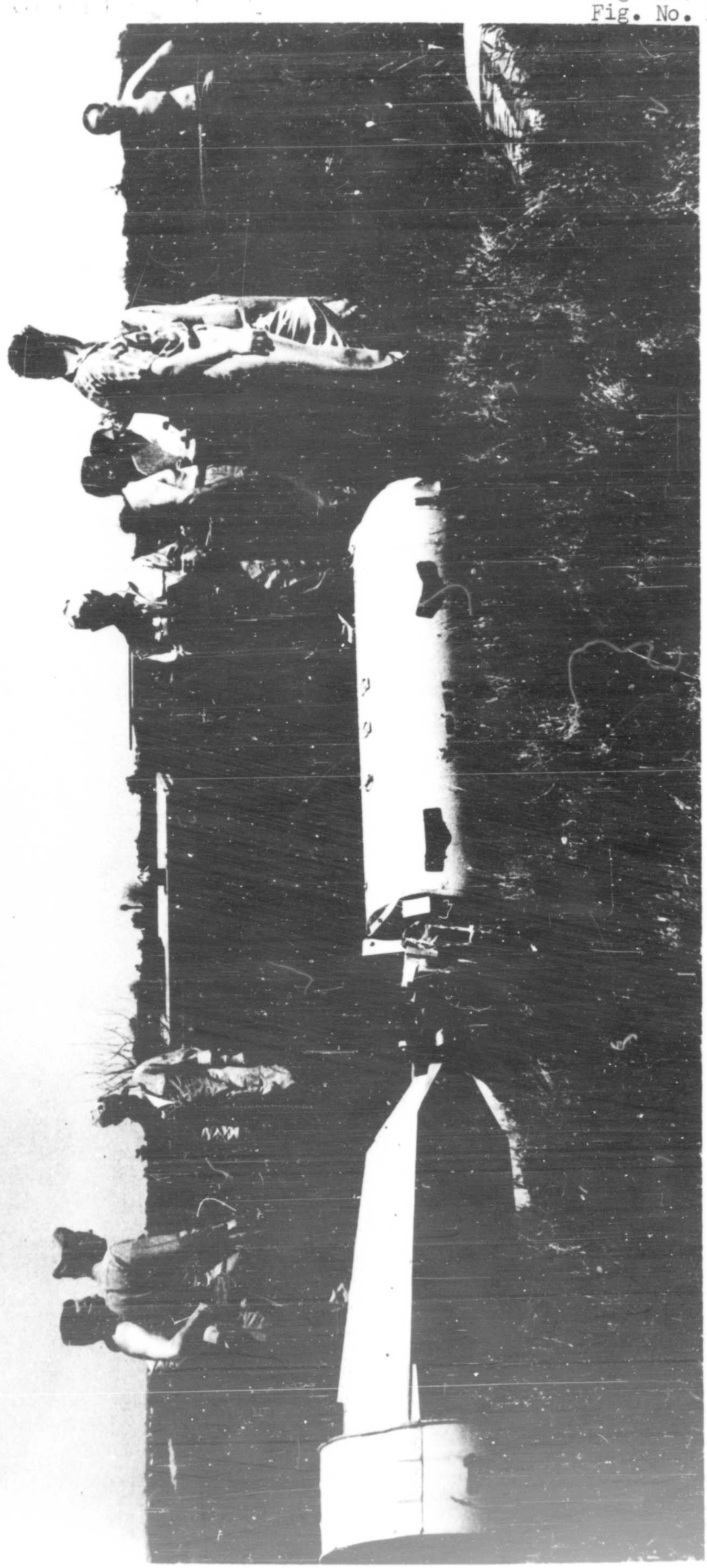

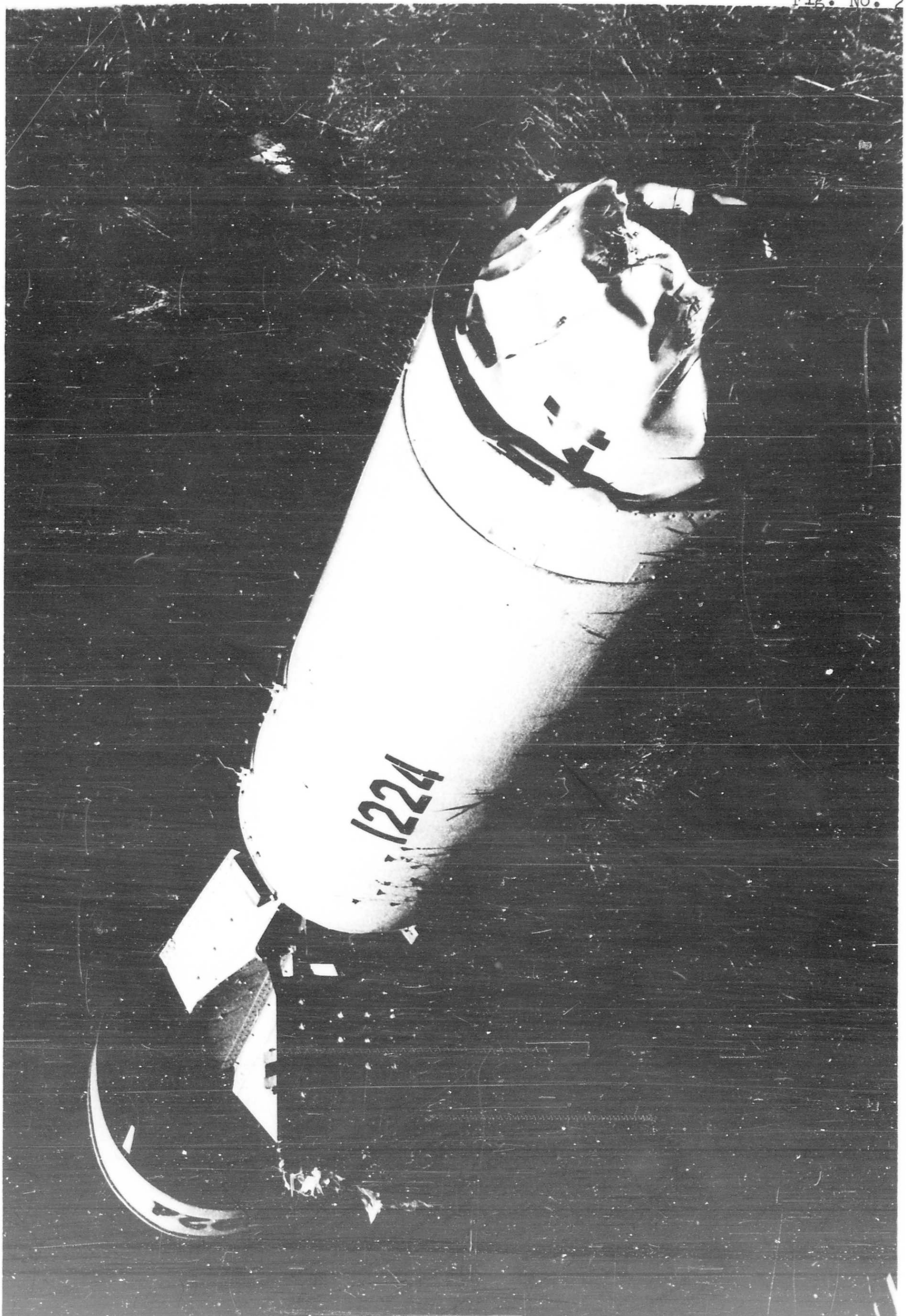
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FIG No. 3

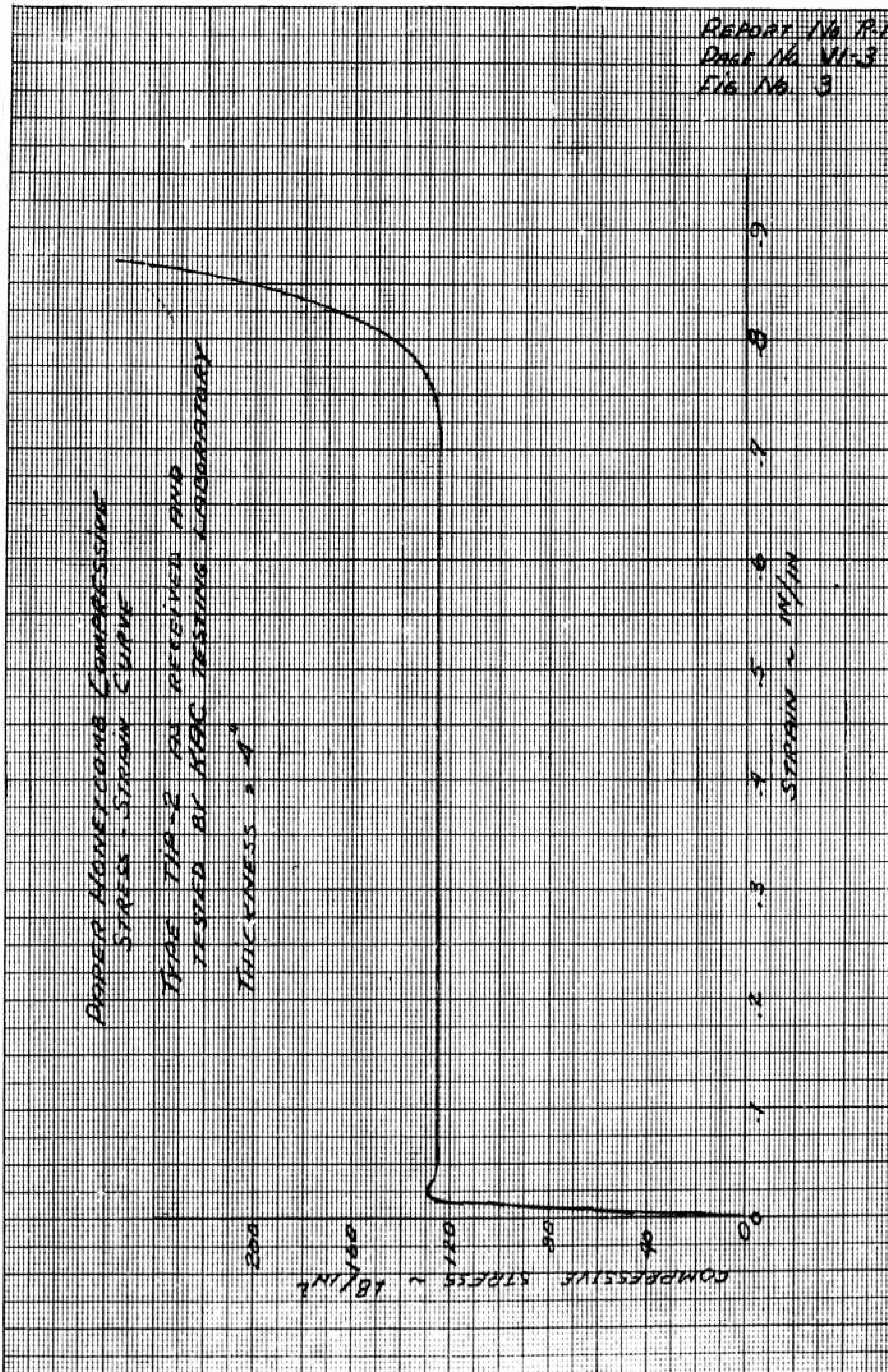

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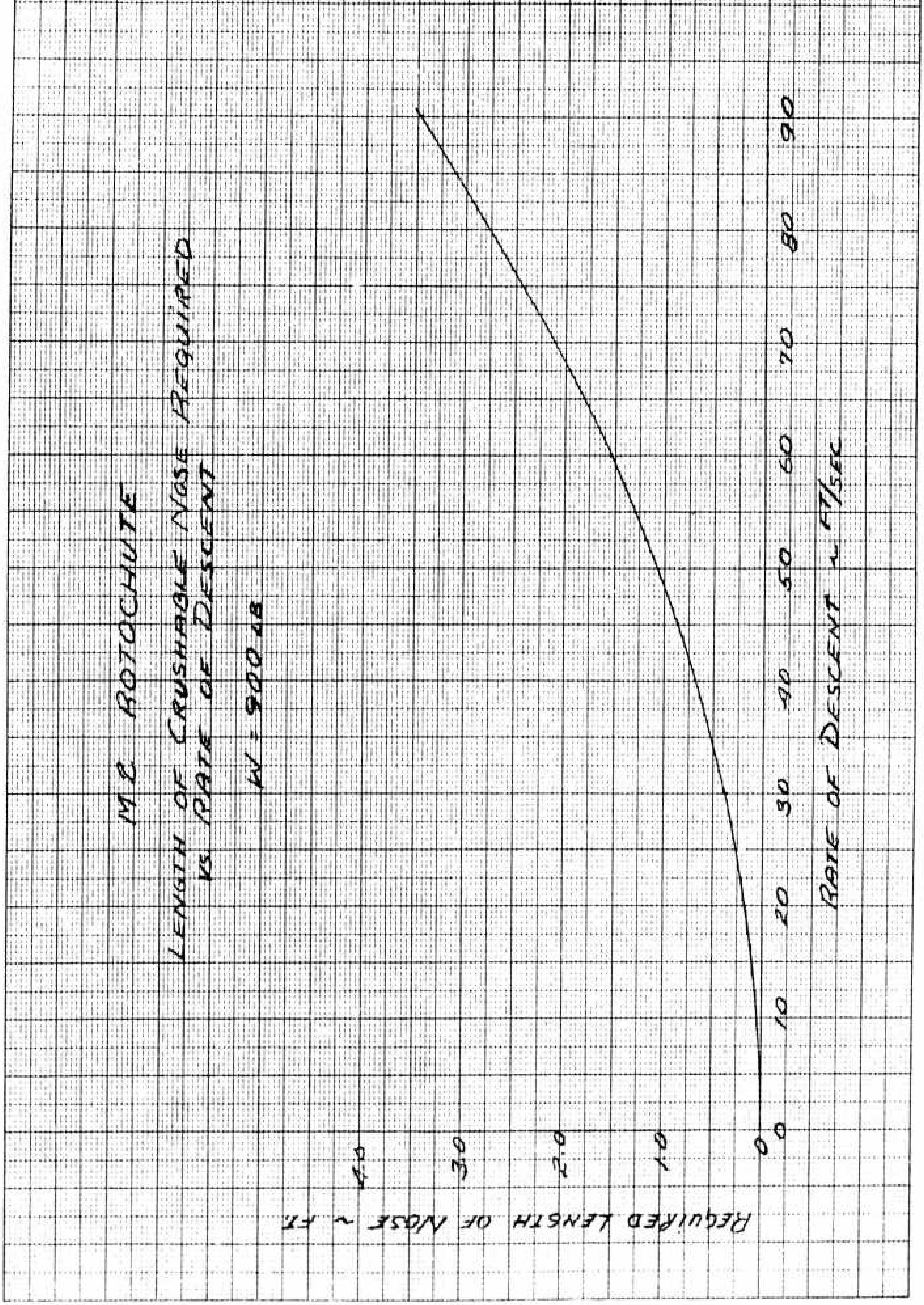
FIG. NO. 4



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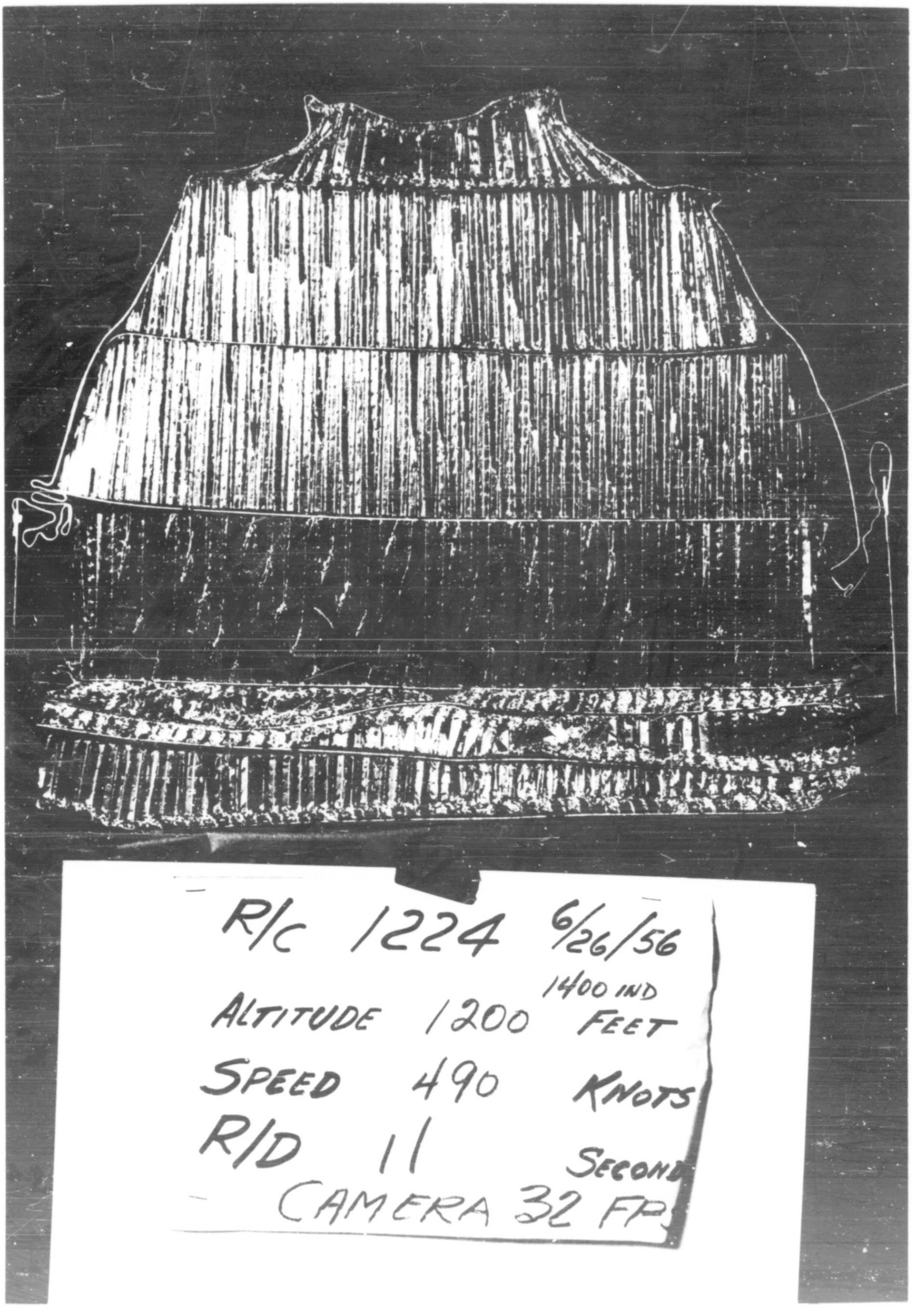

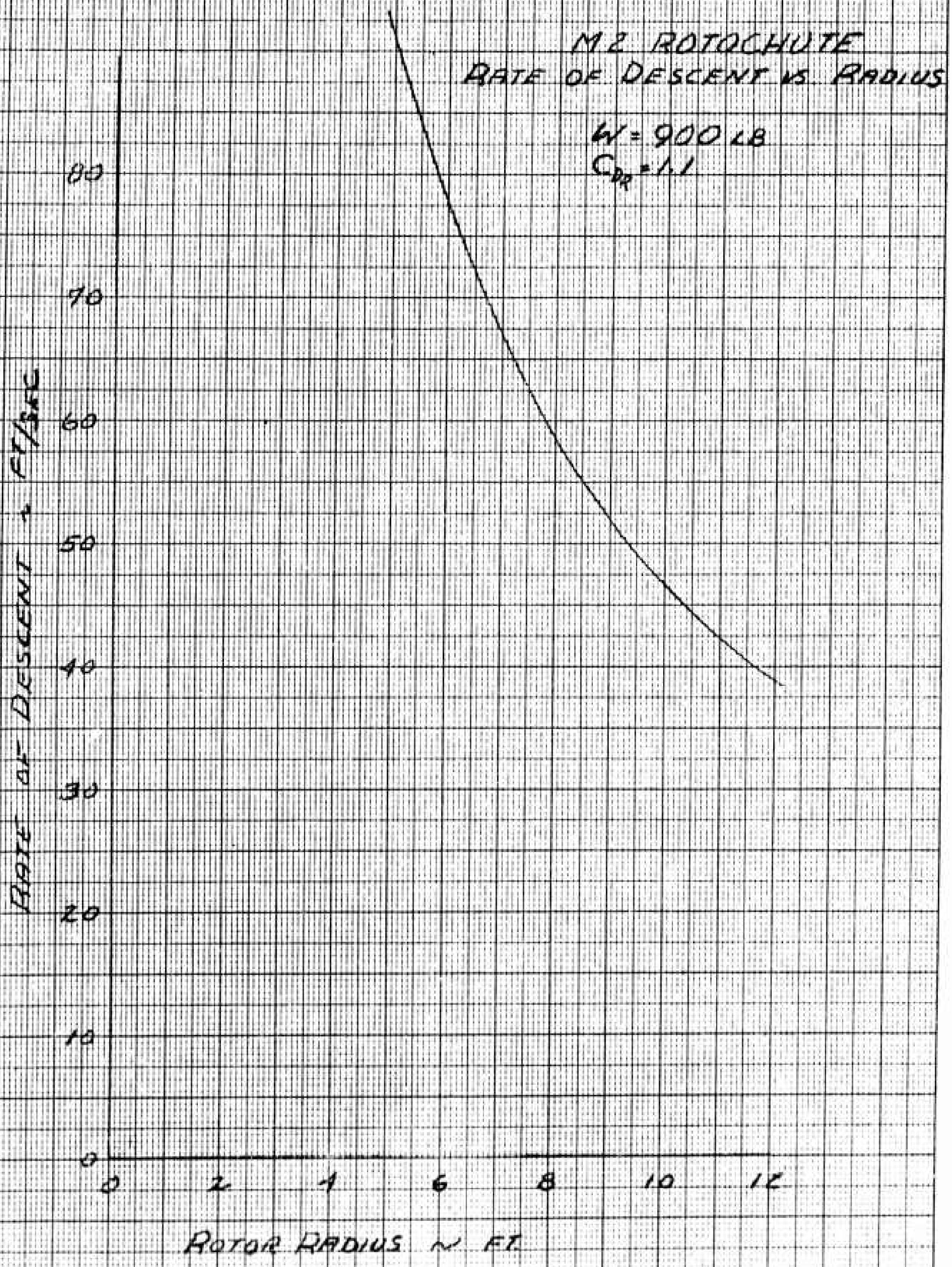
M2 ROTOCHUTE
RATE OF DESCENT VS RADIUS
W = 900 LB
C_{D_R} = 1.1
80
70
60
50
40
30
20
10
0
RATE OF DESCENT ~ FT/SEC
0
2
4
6
8
10
12
ROTOR RADIUS ~ FT.

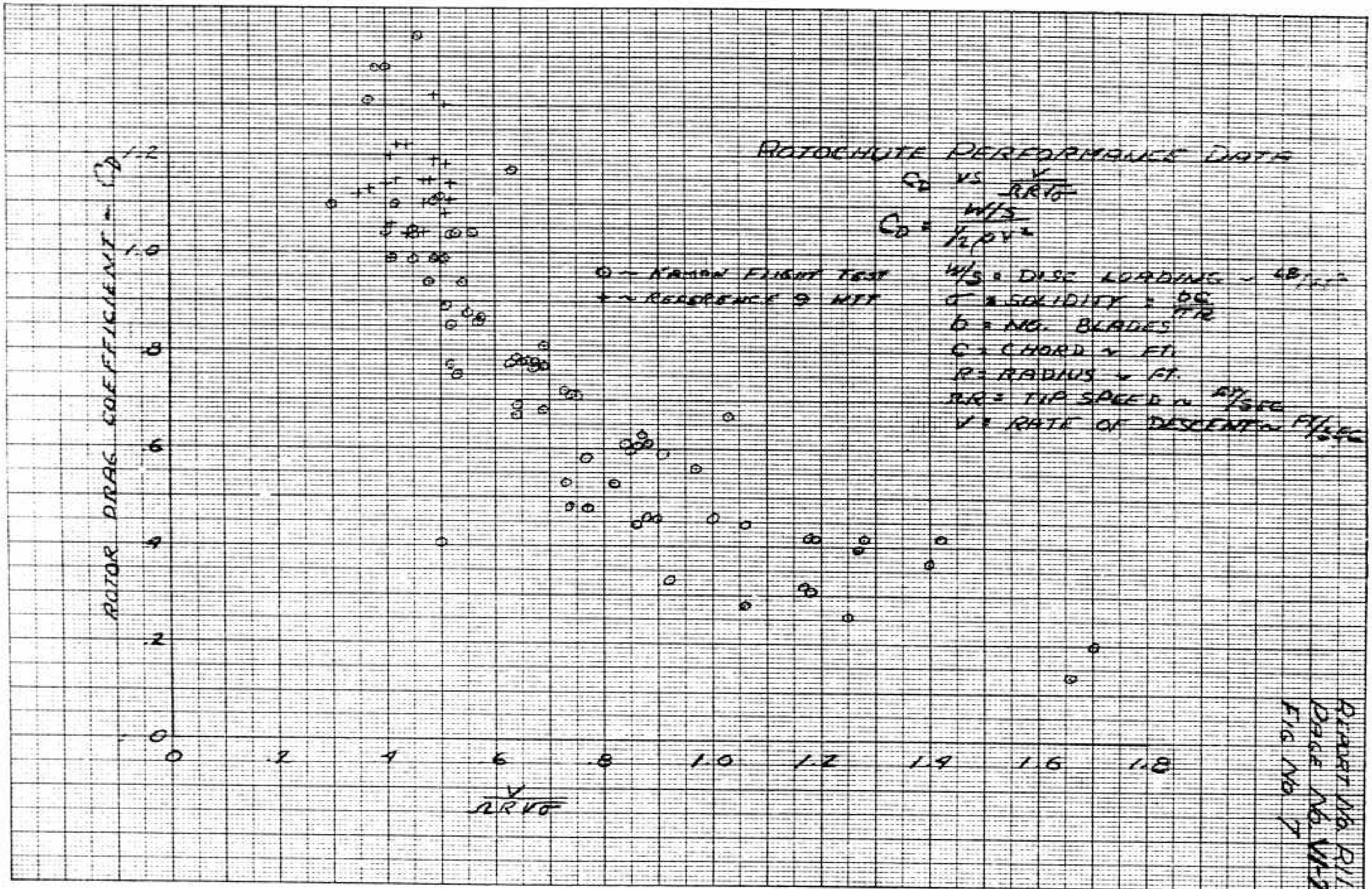

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FIG No. 7

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FIG NO 8

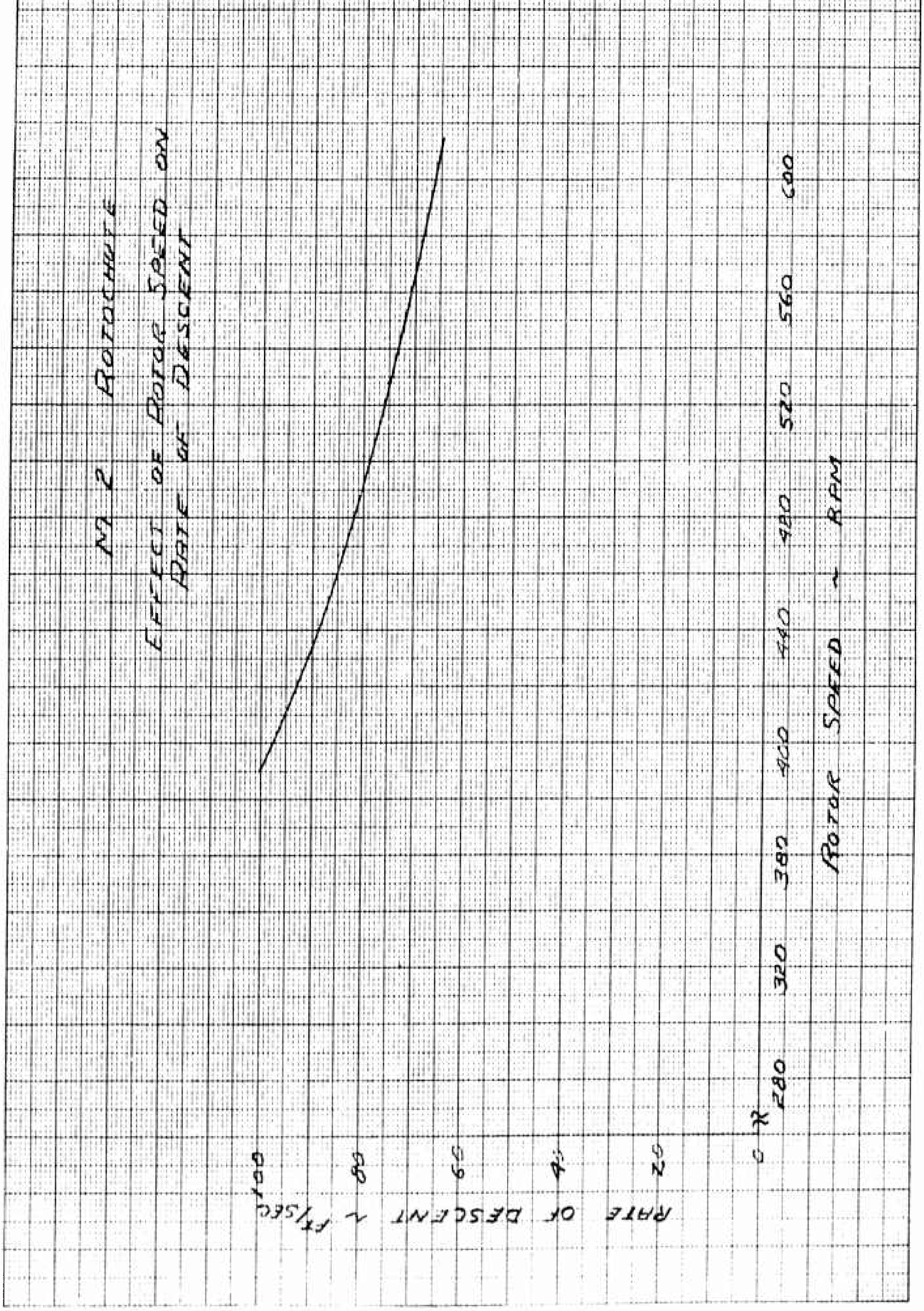

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FIG No 9

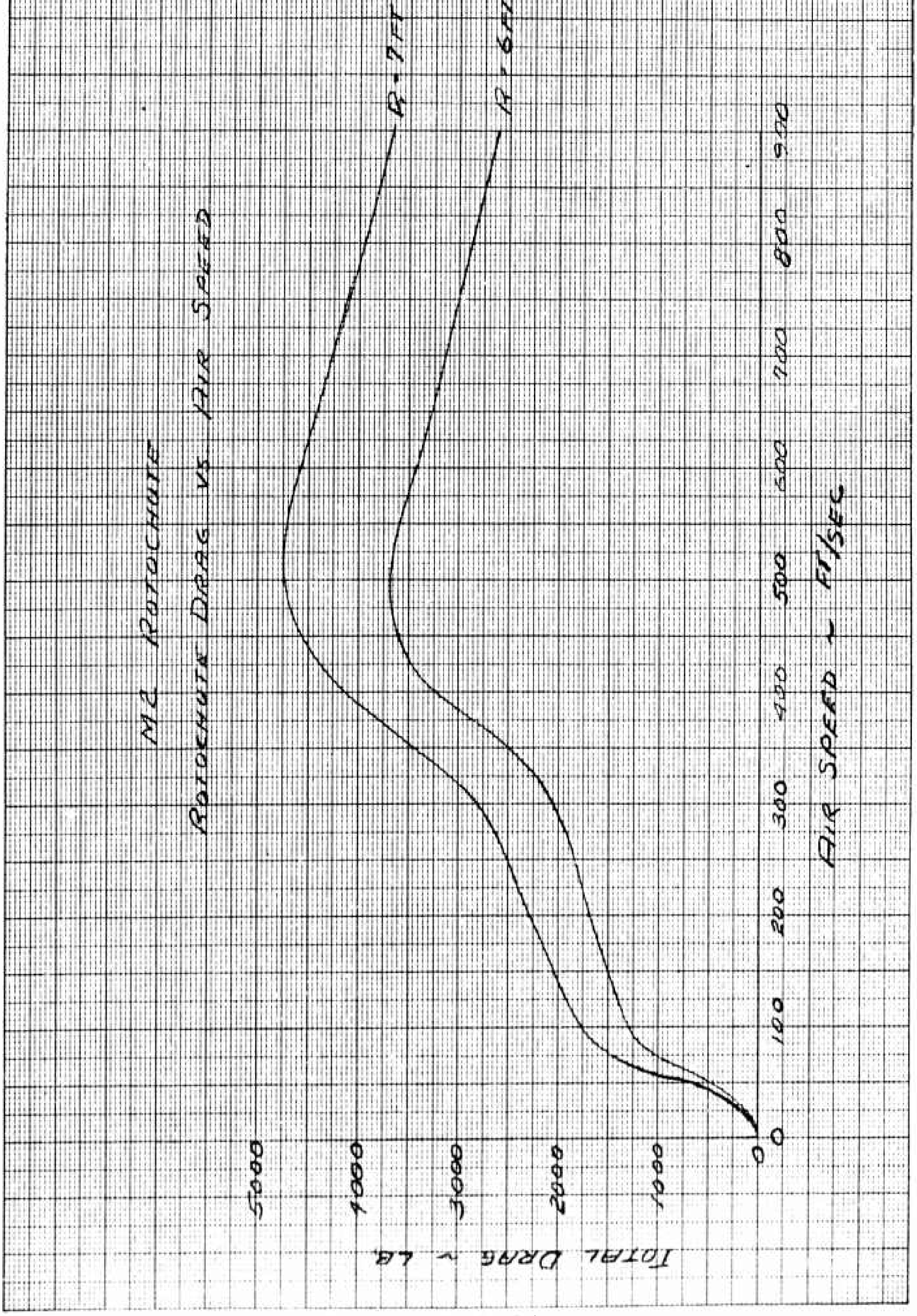

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Fig No 10

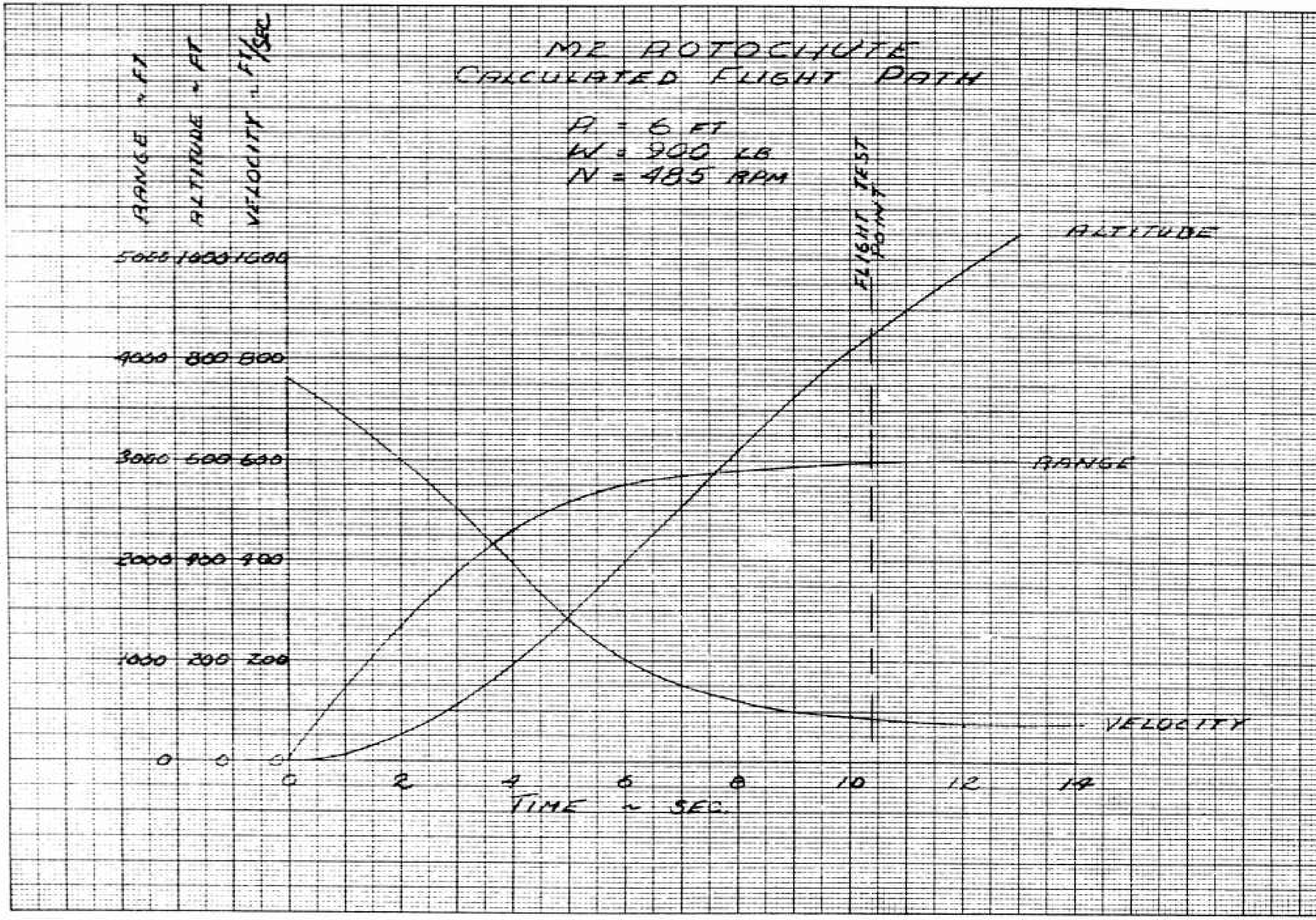

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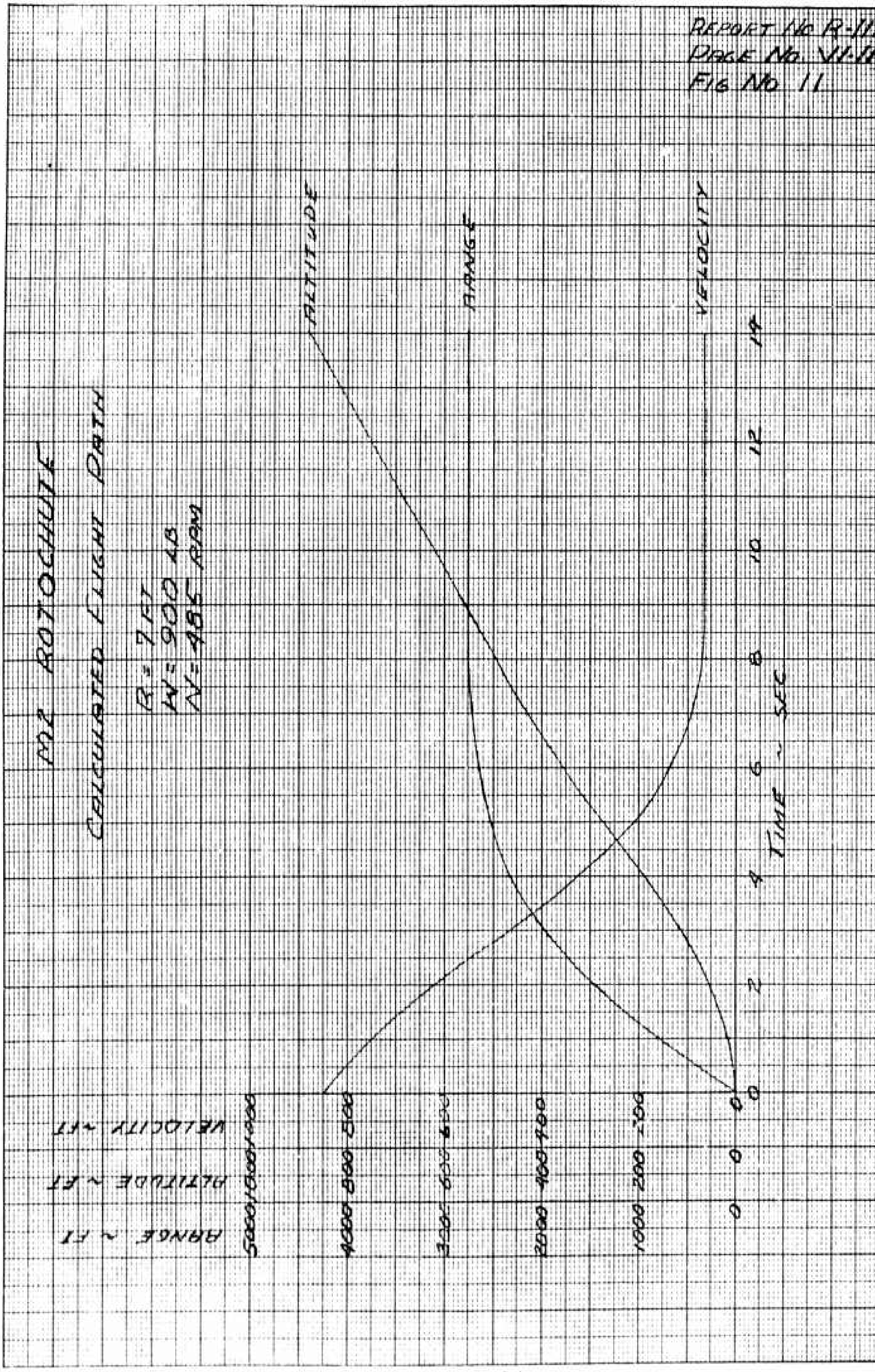
Fig No 11



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